

Integration of an expert system for security assessment into an energy management system

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An expert system is proposed for the effective use of currently available management software. The implementation of an expert system for contingency evaluation and its demands with respect to the knowledge representation are discussed. Experiences with the integration of the powerful expert system for contingency evaluation in an existing EMS are presented.

Keywords: expert system, EMS, security assessment, knowledge representation, contingency evaluation, integration of expert system

I. Introduction

The effective use of power application software (PAS) within an energy management system (EMS) requires intensive training and skill by the operators. In a recent survey¹ it has been found that many important application tools are not fully used because under normal operating conditions they are of restricted importance, while before or during disturbances it is difficult to include them in the operator's decision-making process. It is believed that this situation may be improved by two approaches:

- dispatch training simulator for the effective handling of the available EMS under a large variety of disturbance scenarios²;
- integration of expert system tools into the EMS.

This paper deals with a specific aspect of network control using an expert system approach within the EMS.

The functionality of an expert system within the EMS is described. Aspects of the knowledge representation are discussed with respect to the performance of the expert system in on-line applications and its user-friendliness. A powerful expert system for contingency evaluation is built. Experiences with the implementation of the expert system and its performance are reported.

II. Functionality of an expert system within the EMS

Figure 1 shows a simplified diagram of a modern EMS consisting of primary and secondary analysis.

The powerful tools of secondary analysis at the operator's disposal contain application functions such as contingency analysis, operator load flow, short-circuit analysis, stability analysis, and optimal power flow with security constraints. Currently available EMS do not provide the operator with support as to how and when to use which secondary analysis function. Nor do they offer any interpretation of the results with respect to the actual operating state.

Such deficits of modern EMS can be overcome when a knowledge-based system is integrated into the secondary analysis as shown in Figure 2. The expert system transforms the information on data acquisition and state estimation for the operator relying on the power application software. The operator communicates with the power application programs through the expert system, which offers a kind of dialogue depending on the

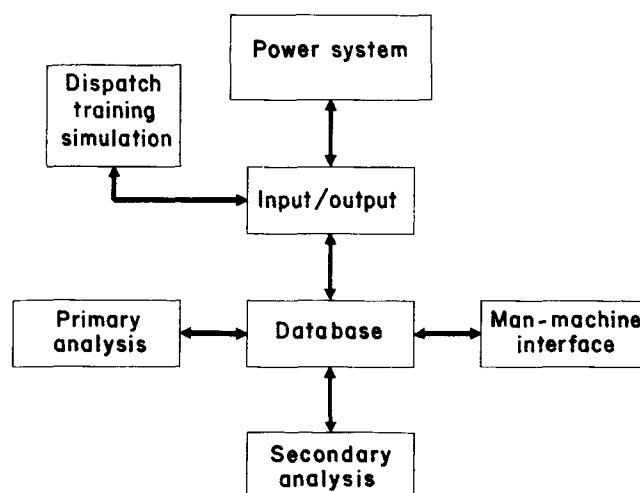


Figure 1. Schematic diagram of EMS for network control

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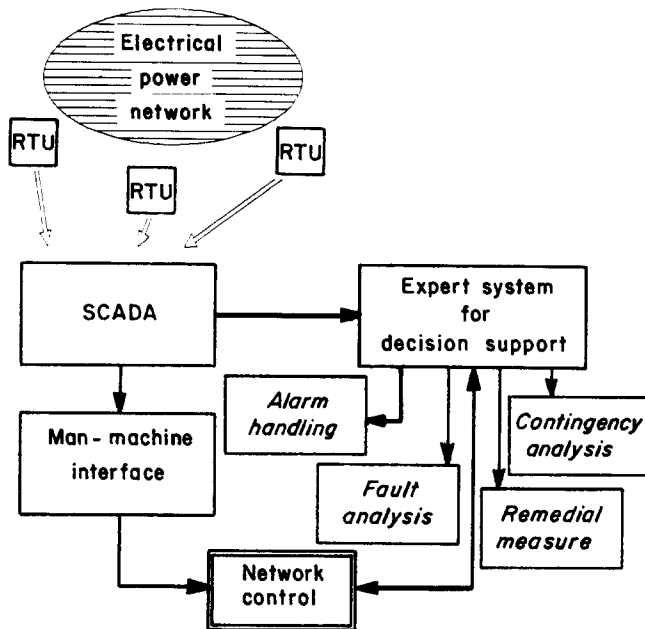


Figure 2. Expert system as part of a new EMS

present system operating state. It is important to emphasise that the expert system does not replace the operator, nor is it mandatory for the operator to use the expert system.

The functions of the expert system shown in Figure 2 include:

- continuous evaluation of the system state with respect to the classifications 'normal', 'alert' and 'disturbed';
- suggestion of feasible preventive or corrective actions with respect to the present system operating state;
- information compression in case of a network disturbance including fault analysis and fault location;
- proposals for adequate load management if ripple control is available in system operation;
- evaluation of switching operations proposed by the operator.

The expert system does not replace any of the well-developed algorithmic solutions of the secondary analysis. However, it offers a powerful and effective use of these programs.

It is the object of this paper to solve the problem of contingency selection by the use of an expert system as a first step towards the realization of the decision support system shown in Figure 2. The contingency list established depends on the actual operating state of the power system. This problem is particularly suited to an expert system approach because it can be readily verified by means of algorithmic methods. The performance achieved shows that a heuristic, rule-based approach leads to a rapid and reliable determination of critical contingencies. Furthermore it offers a good basis for the next realization step where preventive and corrective measures will be derived by an extended expert system in order to maintain the operating state of the power system within the $(n-1)$ security level. Compared with a complete contingency list, evaluation of the rule-based approach offers interesting insight into the reasons why the power system state might not be normal under certain conditions.

III. Knowledge representation

Every knowledge base of an expert system for applications in electrical power networks must contain three types of knowledge (see Table 1). Considering the on-line application of the realized expert system, changing network data must be distinguished from unchanging facts, e.g. information on certain devices.

An experienced operator quite often detects critical network conditions without applying any skilled analysis tool but simply by putting some measurement data and his experience together. Asked to explain his decisions he usually will give rules in a well-known IF...THEN structure. Within the expert system for energy management application the representation of knowledge is quite similar to these heuristic rules given by an operator.

The knowledge base, e.g. for the classification of contingencies, contains a collection of readable statements describing typical outage situations that might cause voltage disturbances, overloads or islanding following the same IF...THEN structure. Figure 3 gives an example of a typical statement to be found in a knowledge base for contingency evaluation.

By applying previously defined statements (true if all AND-combined conditions of their IF part are true) and statement groups (true if one of their OR-combined statements is true) in the IF part of a statement it is possible to describe even complex conditions³.

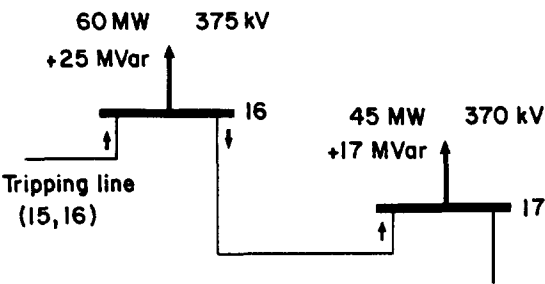
This concept of knowledge representation allows the implementation of both factual and generic statements. Factual statements apply clearly defined topology information and measurement data to form the IF part of rules, whereas generic statements (see Figure 3) give a more abstract description of certain situations. During the inference process the inference engine applies generic rules to all fitting data found in the network database. Obviously the implementation of generic statements is much more powerful than the factual description of a great number of cases.

As the example shows, the pure logical knowledge representation has been enhanced in different aspects (see Figure 4). These enhancements aim at improving the user-friendliness of the system as well as speeding up on-line applications. The inference engine controls implicit links within the IF part of a statement (see Table 2). This permits the formation of lists of conditions similar to the natural-language expression of the statement by putting together previously defined statements (leading to a hierarchical structure of statements). Generic statements provide a much more efficient coding of rules

Table 1. Components of the knowledge base

Knowledge	Type of information		
	Data	Facts	Rules
Problem description (network database, alarm messages etc.)	*	*	
Knowledge of the problem domain (limits, behaviour of protective devices etc.)		*	*
Description of solutions (generic description of critical outages, typical alarm patterns etc.)			*

than an implementation in forms of logical specific facts. Time-dependent intermediate results of the inference process are explicitly controlled in order to minimize the response time and to avoid reasoning on inconsistent data. Optimization of performance is effected by using different modes of inference and by controlling the generic behaviour of statements. An optional explanation facility provides explanation of successful as well as of failing



Generic description of operating condition:

A voltage limit violation must be expected after the tripping of a line

- A transmission line is switched off* ☐
- ^ *The receiving node of this transmission line is a load node with only one remaining line* ☐
- ^ *This node has a small undervoltage* ☐
- ^ *The transmission line supplying this node leads to another load node* ☐
- ^ *This node has a small undervoltage* ☐

Figure 3. Example of a generically coded heuristic rule

Simple knowledge

IF...THEN...statements built by applying: AND, OR and NOT
generic and factual statements

full logic
power
of rules

+ extensions for user-friendliness

statements are represented by texts
implicit links between statement in the IF part of rules

complex preconditions might be represented as IF...THEN... statements themselves (= > box of bricks)

input of new statements by combining already defined statements (texts) in IF parts of new ones

legibility
natural-
language-
like

hierarchy
of rules

knowledge
base
maintenance

+ extensions for on-line applications

control of intermediate results with respect to changes in preconditions

explicit control of the generic behaviour of each statement

basic statements apply algorithms, databases or user questions

validity

speed up

data
acquisition

Figure 4. Aspects of the realized knowledge representation

inferences in order to increase the operator's confidence in the results of the expert system.

IV. Implementation aspects

Expert system applications are not intended to replace the powerful algorithmic software applied in EMS environments. Therefore there is a strong demand for an optimal interaction between available EMS software and new expert system applications. The integration of algorithmic and rule-based approaches must be supported by an expert system shell applied for power applications (see Figure 5).

The full integration of an expert system into an existing EMS is a complex and time-consuming task. Most important is direct and fast communication between the expert system and the static and dynamic data within the EMS database. The implementation of expert systems has to take this communication link into consideration. In many cases this requirement prohibits the use of a

Table 2. Six types of statement applied to provide a natural-language-like form of implementing rules

	Explicit information dealt with	Explicit information generated	Type of statement
There is an overload line	0	0	☐
This line is overloaded	1	0	☒
A line	0	1	☐
The load of this line	1	1	☒
These two lines are in parallel	2	0	☒
The line carrying more load	2	1	☒

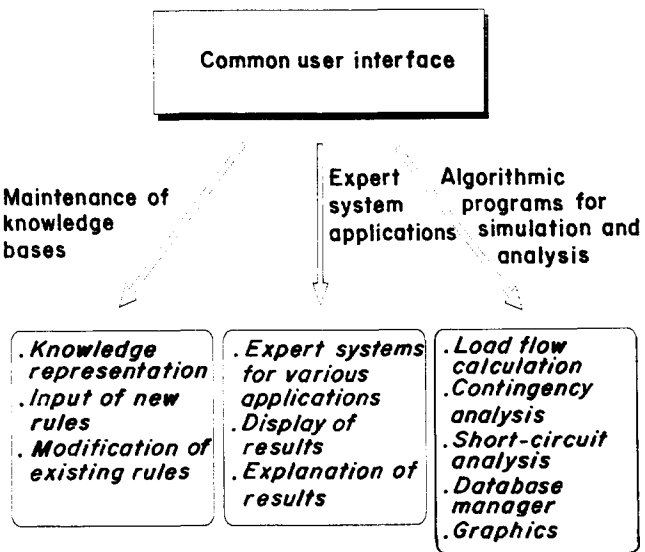


Figure 5. Shell for expert system in power applications

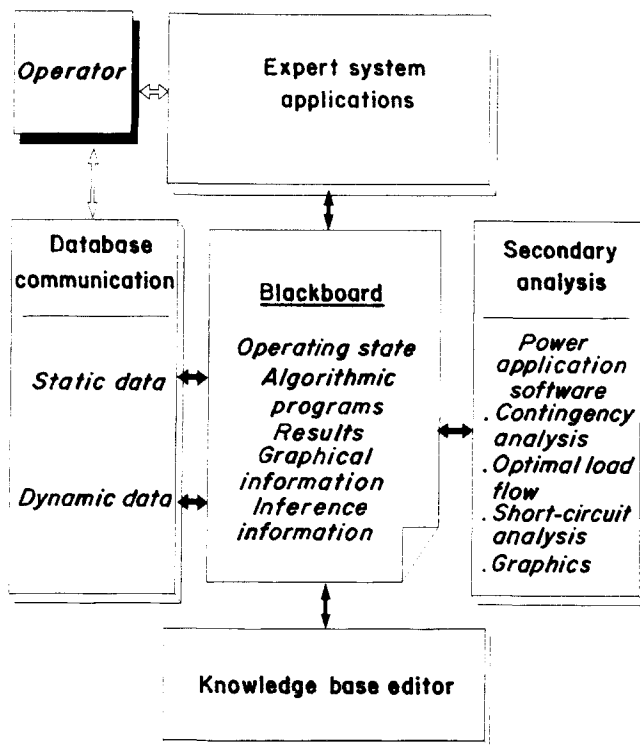


Figure 6. Communication between the EMS and all parts of the expert system

general-purpose expert system shell. Hence it is proposed to use the software and communication structure using a blackboard approach as shown in Figure 6 (Reference 5). Good experience has been obtained with implementation of the expert system in PROLOG.

The expert system is realized as a multi-program system. The chosen principle of communication between all programs of the expert system provides the opportunity to link the system easily to an external data source via an interface program (e.g. via a local area network).

An expert system receiving information by asking the operator many questions is of course not acceptable for control purposes in EMS centres. Expert systems for on-line purposes must provide facilities to acquire the information needed automatically during the inference process. Within the expert system presented the concept of basic statements is used to provide the inference process with the information needed. Basic statements give the opportunity to use such diverse sources of information as databases, algorithmic programs, and measurement units. An automatically generated request to the operator does the same in the case of disturbed or missing data links or non-available algorithmic programs.

The principle of knowledge representation and the inference engine realized allow one to establish expert systems simply by applying the natural-language-oriented knowledge-base editor to combine previously defined statements to the IF parts of new statements. Decision trees are easily implemented by basing them on basic statements. If necessary, new basic statements might also be implemented with the knowledge-base editor. If a communication link between the new basic statement and a new information source is to be realized, deeper knowledge of the expert system is needed.

Because of warranty and other non-technical aspects, the modification of the knowledge base is normally separ-

ated from the operator. Nevertheless the knowledge-base editor is generally accessible to the operator in display mode because insight into the knowledge base gives a good understanding of the system.

The inference engine evaluates knowledge bases read from a file. It does not carry any application-dependent characteristics. Therefore it could successfully be applied to realize expert system prototypes for different purposes:

- evaluation of contingencies;
- generation of preventive and remedial actions;
- alarm handling and fault location;
- information systems.

Applying the principles of knowledge representation described above, an expert system has been realized for the classification of contingencies. Using generic and (as few as possible) network-specific rules the expert system automatically provides a list of all operating equipment whose failure would affect the $(n-1)$ security principle. The expert system tells the operator which elements are critical with respect to overloading and voltage limit violations.

During the implementation phase the contingency list was evaluated by means of a fast load flow program (Figure 7). Testing the knowledge base by applying it to some 10 000 outages in several networks and quite different load and topology situations, and manually comparing the expert system's results to the algorithmic outage evaluations, was part of an iterative optimizing process leading finally to a knowledge base carrying nothing but generic, non-network-specific rules and allowing the expert system to detect more than 97% of all critical outages.

V. Practical experience

The expert system prototype has been applied to the modern energy management system of a German utility

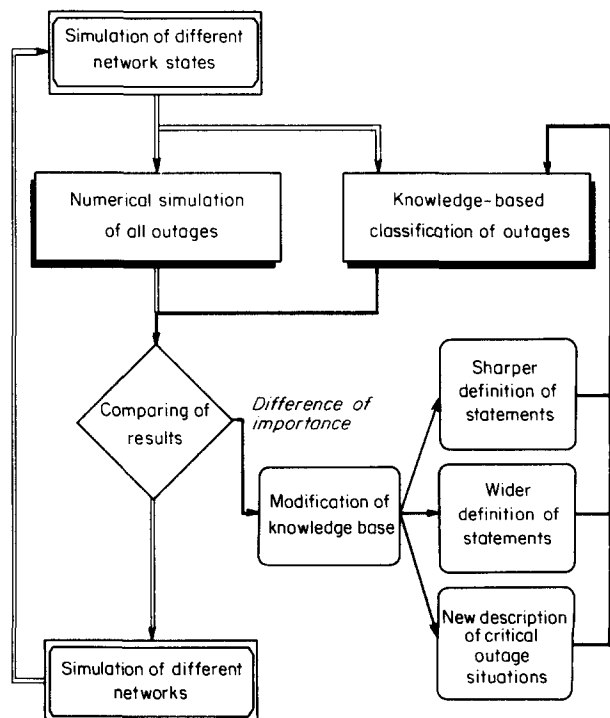


Figure 7. Testing and optimizing the knowledge base for contingency evaluation

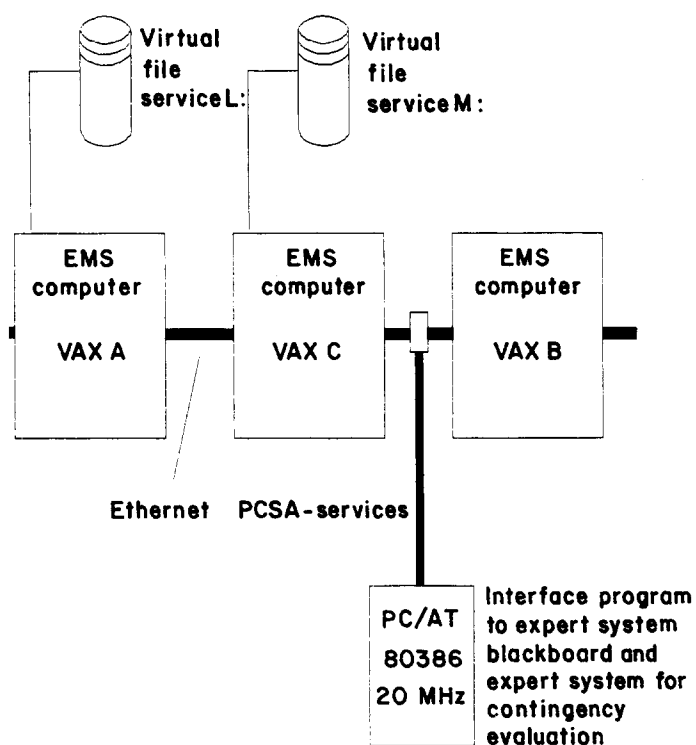


Figure 8. Communication between the expert system and the EMS

operating an extensive 110 kV network (120 nodes, 190 lines).

The utility as well as the developer of the EMS are interested in the field test for a number of different reasons, as follows.

- Even if there is no problem with the $(n-1)$ security nowadays, an expert system like this might be helpful in maintenance work or switching operations.
- The user is interested in the expert system technology because he believes it to be advantageous to have an explicit representation of what determines a program's function together with an optional explanation facility.
- In the same sense the developer is interested in the expert system technology and a knowledge-based solution of the classification of contingencies.
- Finding ways of applying knowledge-based algorithmic solutions developed by external institutes to modern energy management systems is another important reason for the developer to support the field test.

In a first step of integration the expert system for establishing the contingency list has been implemented on separate hardware. The data communication with the EMS database uses an EtherNet interface (see Figure 8). Data from the state estimator are provided every 15 min or after operator request.

By adding few network-specific rules and by retracting other rules that are irrelevant for the specific network, the performance of the system could be improved until nearly all critical outages (99.9%) occurring during the field test or simulations were detected. The effort put into the network-specific optimization of the knowledge base can be roughly estimated as about 5% of the manpower put into the generic, non-network-specific knowledge base.

Using generic and a few network-specific rules the

expert system automatically provides a list of all operating equipment whose failure would affect the $(n-1)$ security principle. Linked to the energy management system, the expert system tells the operator by colouring a network graphic which elements are critical with respect to overloading and voltage limit violations. On request the expert system justifies its decisions individually. After that the contingency list might be evaluated by means of an algorithmic load flow program. Typical results are shown in Figure 9.

The performance of the expert system is characterized in Table 3. The expert system is implemented in PROLOG and runs under DOS on any PC with 640K working memory. Table 3 gives the time consumption using a PC/AT (20 MHz). Applying the faster 486 PC/AT (33 MHz) allows one to provide a contingency list for the same network within less than 40 s.

In the rare cases of underaction the knowledge base must be improved by adding the description (generic if possible) of the critical outage situation. By doing this, the quality of the knowledge base grows as the experience of the operator itself does.

This implementation is the first part of the expert system proposed for the support of network security functions (see Section II). Based on the experience with

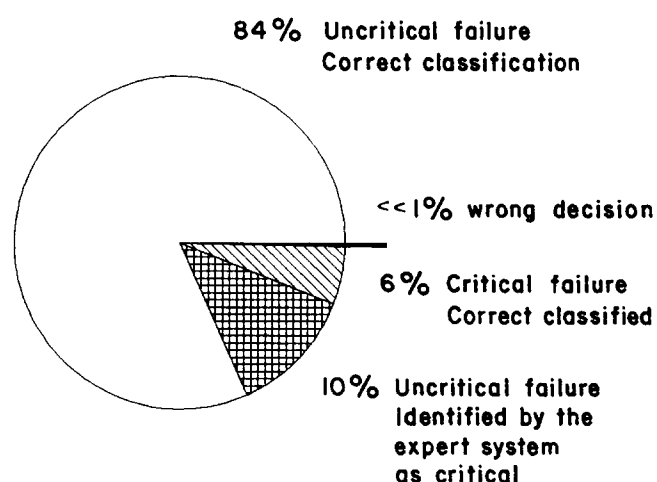


Figure 9. Typical results of the classification of contingencies

Table 3. Experiences with the knowledge-based evaluation of outages

Number of statements in the knowledge base	Approx. 200
Inference process for classifying a contingency	Maximum 2 s Average 0.6 s
Finding the contingency list for an 110 kV network with 120 nodes and 190 lines	< 100
Overaction (requesting an algorithmic outage simulation although outage is uncritical)	About 10%
Underaction (missing critical outages)	<< 1%

the contingency selection and the appropriate explanation feature the next step will include the determination of adequate preventive and corrective actions for each critical contingency by applying an expert system prototype recently developed on the basis of the same knowledge representation and inference engine.

VI. Results

As a consequence of an analysis of the effectiveness of the use of power application software in modern energy management systems, the implementation of an expert system is proposed as one approach to improve the situation.

Starting with an analysis of the specific demands of heuristic knowledge implementation for EMS applications a concept of knowledge representation has been developed. The principle of knowledge representation by building hierarchical IF parts of rules by putting together previously defined statements and basic statements (see Table 2) permits the application of different sources of information during the inference process. The implementation of generic and factual statements is supported. In order to allow on-line process applications of expert systems the inference engine controls the time dependency of intermediate results. Supersets of the pure logic allow the implementation of links between different conditions in the IF part of a rule. By applying these links the representation of knowledge within the knowledge base closely approaches the natural-language-like form of heuristic knowledge given by domain experts. The concept of knowledge-based programming has been applied for the realization of an expert system for contingency evaluation as a first step of the development of a decision-support system for the use of power application software.

The implementation of the expert system prototype in the energy management system of a large German utility yields good results, especially because of the fact that the adaptation of the knowledge base took only about 5% of the effort put into the development of the non-network-specific knowledge base.

Good success and experiences obtained with the development and test of the expert system described above will help to transfer expert system technology to other applications in electrical power engineering. In particular, the applicability of the inference engine to various expert system solutions is one important advantage of the expert system technology. The prototypes for different applications implemented up to now have been extensively tested and give evidence for the power of knowledge-based problem solving⁶.

Because of its importance the fact should be underlined that heuristic-based solutions, as well as human experts, will in principle not guarantee 100% error-free answers. Nevertheless, the application of heuristic (i.e. incomplete, simplified and limited validity) knowledge might be helpful when analytical or algorithmic solutions are too complex or not yet known. Heuristic, knowledge-based solutions always aim at an improvement in, not at the replacement of available algorithms. The software development of the next decade has to improve the facilities of the integration of numeric, mainly algorithmic programming with the technique of knowledge-based problem solving.

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